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Performance Analysis of a Microthruster for Satellite Applications

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Abstract

Scientific space missions require a very high accuracy of positioning and orientation of the satellites in order to meet their objectives. Such accuracy can be obtained through a set of positioning thrusters, which need to be able to generate very low forces with high precision. This result can be obtained using cold gas thrusters. A method for the design and the forecast of the expected performance of such thrusters will be presented.

Keywords: Microthruster, Satellite Positioning

1. Introduction

Modern scientific satellites require a very accurate positioning system in order to be able to perform their missions. This is due to the need of maintaining a precise orientation and/or position with respect to an inertial reference frame despite possible disturbances (deriving from gravitational influence, solar winds, etc.). In order to obtain such accuracy, the positioning engines must be able to provide very small thrusts with high precision in response to a suitable feedback system based on inertial position and orientation sensors and implemented by a dedicated software. The needs of recent ESA missions, like GAIA, LISA Pathfinder etc., call for systems able to provide thrusts as low as 0.1 μN with a dynamic range of the order of 10000, i.e. reaching to a maximum thrust of 1 mN. In addition, the thrusters must be able to undergo a large number of on/off cycles, provide long as well as very short working periods during which they may be required to vary the thrust according to the instructions of the feedback system, maintain their efficiency throughout the life span of the satellite, require very little energy for their operation and cause little or no electromagnetic interference. These operational parameters are so demanding that no off-the shelf system was available at the time when the GAIA mission was conceived (around year 2000; the mission was then launched in 2014), and were therefore developed specifically for this mission by Leonardo S.p.A. (before 2013 Thales Alenia Space) with the technical support of INRIM (then CNR-IMGC). One of the technological developments that were performed was the fluid dynamical analysis of the flow within the thruster nozzle, which allowed to optimize the shape and forecast its performance.

2. The Principle of Fluid Dynamical Thrusters

In order to meet the requirements described in the previous paragraphs, it was decided to develop a positioning device employing the principle of fluid dynamical thrusters [2], better known as Cold Gas Thrusters. This type of thruster is based solely on the conversion of the pressure energy of a compressed gas into thrust; indeed, when a gas at a pressure expands towards a condition of lower pressure it accelerates, and it is possible to take advantage of this acceleration if it is made to happen within a nozzle. The simple jettisoning of gas through a hole would actually provide some thrust, but the efficiency of the process would be very low since most of the expansion would happen outside the device and could not be transferred to the satellite in a controlled way. On the other hand, the expansion within a nozzle allows to recover most of the pressure energy and to convert it into a force with a precise direction. A principle schematic of the system is presented in Fig. 1:

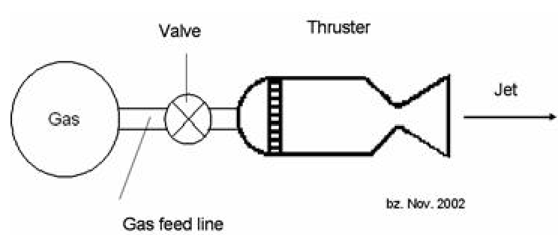

Figure 1: Generic schematic of a Cold Gas Thruster.

Like other available methods of controllable micro-thrust generation, the cold gas concept requires a reservoir of compressed gas and an accurate flow regulation system. The latter had been developed by IMGC-CNR and industrial partner in previous projects [3, 4] and could be transferred to this device without problems. The main advantage of this type of thruster is that it does not require any electromagnetic field to accelerate the gas; this implies that its energy requirements are very low and that no charged particles or electromagnetic disturbances are generated. Moreover, the system is very reliable and repeatable, thus providing an excellent actuator to the positioning control. On the other hand, the maximum possible specific impulse is quite low, thus requiring a very careful nozzle design in order to reduce losses. This drawback, due to the fact that the required thrusts are very little, can be considered minor in the application described here. Indeed, the method will require a larger quantity of gas with respect to other concepts, but the increment of reservoir mass, although large in relative terms, is moderate in absolute terms and can be offset by the suppression of the acceleration devices. In the case described here, the cold gas thruster was realized by designing an axisymmetric nozzle fed by a double-cone regulator driven by a piezoelectric actuator; the system was downstream of a regulation valve which allowed it to be fed with a constant pressure. Between the regulation valve and the double-cone, a thermal flow mass sensor allowed the measurement of the propellant flow rate Q to be provided to the control system. Since the datum available to the control system is Q, the performance of the nozzle will be described in terms of the generated thrust (T, expressed in μN) and of the specific impulse ($I_{SP} = \frac{T}{Q}$, expressed in s); both these quantities will be expressed as functions of Q.

3. Computational Approach

The fluid flow within the thruster undergoes a complex evolution (see, e.g., Fig. 2); after the pressure reducer, nitrogen is fed to the nozzle through the double-cone regulator, which generates a convergent/divergent geometry where transition from subsonic to supersonic flow is associated to a large pressure reduction. Following the first divergent, two constant-diameter sections, imposed by building constraints, are present; finally the final divergent drives the second part of the expansion; the thrust is generated in both parts of the expansion in the form of forces applied to the cone and to the nozzle.

As it can be seen (See Figg. 4,5), the system density is relatively high on the first part of the inlet cone, but as the section increases density quickly decreases and it reaches levels of strong rarefaction already during the first expansion.

Methods usually applied in CFD (Computational Fluid Dynamics) are based on the numerical solution of the Navier-Stokes Equations, a set of partial differential equations developed on the basis of the so-called continuum assumption, meaning that the fluid can be assumed as a continuum medium; though, such assumption is valid only as long as the density is sufficiently high. In the case discussed here, the outlet condition is that of a void, therefore the continuum assumption must break down at a point. It will therefore be necessary to employ other methods, based on the analysis of the actual molecular dynamics (Boltzmann Equations). Methods for the solution of the Boltzmann Equations were developed since the 1960s; in the case of extremely rarefied flows, such methods aim at following the path of single molecules (direct Boltzmann methods), but when rarefaction is not extreme the number of molecules is too high for simulation; therefore, in order to simulate such flows, a statistical method was developed by G.A. Bird (see [1]); this method (Direct Simulation Monte Carlo, DSMC) aims at computing the movement of the molecules and their interaction on a probabilistic basis.

In order to analyze the flow existing in the nozzle, where a region of high-density coexists with a portion with low and very low densities, it was necessary to blend continuum methods with a DSMC simulation. To this aim, the flow in the convergent part of the nozzle was simulated using a self-written 2-D axisymmetric Navier-Stokes solver, who provided the flow conditions at the throat section; the velocity profile thus obtained was then fed to the DSMC solver for the analysis of the flow in the main part of the nozzle. The DSMC code used was the DS2V semi-commercial code developed by G.A. Bird [1] for two-dimensional flows, which also allows axisymmetric computations. The code provides as its exit a map of the flow in the analysis geometry; several quantities can be selected for the output. Typically, the quantities that were used in the present work were the flow velocity and density, since they were to be used for the momentum computation. Examples of velocity maps are reported in Figg. 2 and 3:

Similarly, typical density maps are presented in Figg. 4 and 5. Notice the logarithmic scale in the density maps, required by the fact that the density variation is dramatic within the nozzle.

Notice the different scales in the density maps; since the scale is logarithmic, it can be observed that density values in the 5 SCCM case are one order

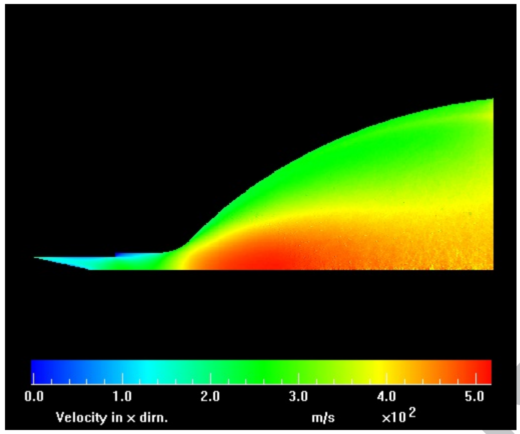

Figure 2: Axial velocity map, baseline geometry, mass flow rate 5 SCCM.

of magnitude lower than in the 50 SCCM case.

Computations were performed for a set of predefined mass flow rates, which were selected in order to cover the range of thrusts of interest. From a numerical standpoint, it must be observed that, depending on the mass flow rate, the density at the starting section of the DSMC simulation varied. The method in principle is valid for any density, but its efficiency degrades when the density increases, therefore for the higher initial densities the computation was strongly slowed down by the high-density region. Unfortunately, the need for a well-defined matching section imposed this approach, but future work on this topic will require a more refined approach for performing the matching between the continuum and the rarefied regions.

The performance was computed by integrating the momentum of the fluid at the nozzle exit section, considering the flow at rest in the initial conditions. In order to keep into account the axisymmetric geometry, circular integration was performed.

4. Results

The method described in the previous paragraph was employed first of all to assist in the definition of the shape of the thruster nozzle. Of course, it was impossible to analyse all the possible nozzle shapes; therefore, based on design constraints and considerations deriving from previous experience, an indicative geometry was selected for the analysis of the dependence of performance on the variation of the parameters defining the geometry. The

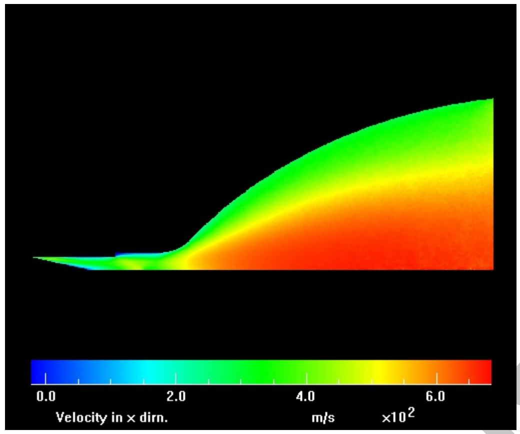

Figure 3: Axial velocity map, baseline geometry, mass flow rate 50 SCCM.

shape that was selected included a conic divergent in the first region, followed by a step (imposed by design constraints), a constant- diameter part and a bell-shaped nozzle; the final bell and its connection to the preceding constant-diameter part were designed as two circular arcs with common tangent at the connection point.

A parametric design method was applied, i.e. the main geometrical values defining the shape of the nozzle (length, exit diameter, curvatures) were varied separately, checking the resulting variation of the obtained thrust and I_{SP} with respect to the results obtained with baseline values of the geometry, and deciding whether every parameter led to a performance maximum or an asymptotic behaviour; for each parameter, the optimal value thus obtained was then selected as the design value. Notice that this method does not guarantee that the obtained nozzle is actually the optimum, since it is possible that non-linear interactions of the parameters effects lead to different performance; actually, the performance of the nozzle thus designed is inferior (although slightly) to the theoretical composition of the results of the single parameters effects; though, the computational and time effort required for the exploration of the whole phase space of the possible shapes would have been excessive.

The evolution of I_{SP} values as a function of the mass flow rate was determined for a set of geometries, which, together with design considerations, allowed to define the geometry of the nozzle. Some of the obtained plots are shown in Figg. 6 and 7. It can be observed that, in all cases, I_{SP} tends to be

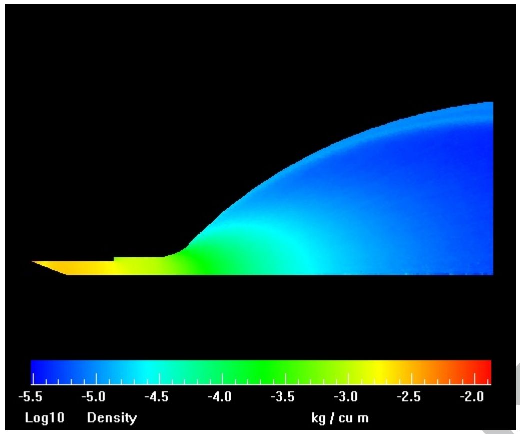

Figure 4: Density map (log scale), baseline geometry, mass flow rate 5 SCCM.

reduced as the flow rate is reduced. This can be explained when considering that I_{SP} is an indicator of the nozzle efficiency in converting potential energy to velocity, and therefore to thrust; now, when the flow rate is lower, the density is correspondingly lower, therefore there will be less collisions between particles and the nozzle wall. Since the collisions, on a molecular scale, are the process that drives energy exchanges, this means that less energy will be transferred from the thermal movement to the organized flow motion; indeed, the temperature mappings showed that in the lower flow rate cases, the gas at the exit was hotter, meaning that the thermal agitation temperature was higher; this in turn means that a larger fraction of the initial potential energy could not be converted to thrust.

Data obtained from these computation were later compared to experimental data obtained from thrust measurements performed on a prototype nozzle using the nano-balance facility available at TAS Torino facilities; results from this comparison are presented in Fig. 8; it can be observed that there is reasonable agreement between the values and the trend of the computed and measured data. The strong fluctuation of experimental data in the initial region is attributed to the high uncertainty levels associated with the extremely low values of the thrust.

This validation is considered quite satisfactory, and provided sufficient trust in the subsequent analysis.

The main advantage of numerical analysis lies, indeed, in the fact that once the numerical results are considered reliable, they allow to perform a

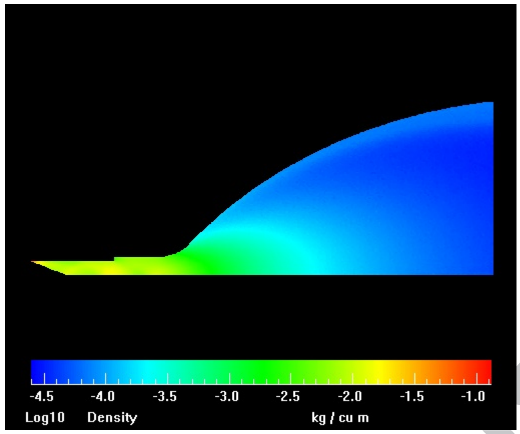

Figure 5: Density map (log scale), baseline geometry, mass flow rate 50 SCCM.

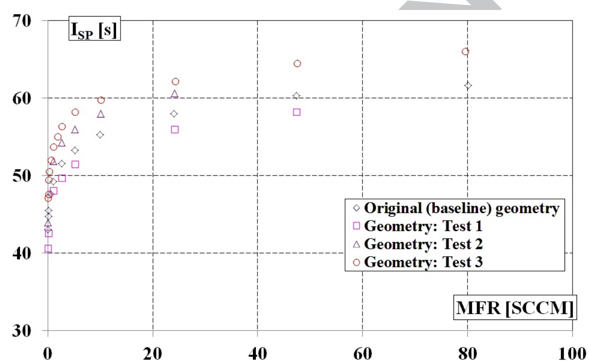

Figure 6: Specific impulse of the thruster as a function of the mass flow rate for some of the tested geometries at reference conditions.

set of computations with well-defined conditions, and in particular to analyse the effect of the variation of various conditions of the flow, which could prove to be very difficult to do through experiments.

One important aspect that could be investigated thanks to the numerical simulations is the influence of external conditions on the nozzle performance. Indeed, the nozzle wall temperature and the gas initial temperature heavily influence the specific impulse produced by the thruster, since both quantities imply a strong variation of the gas energy and therefore of the momentum at the exit. Now, due to the mission profile expected for the satellites to be equipped by the cold gas thrusters described here, both these temperatures can vary in a relatively wide range, implying therefore that the specific im-

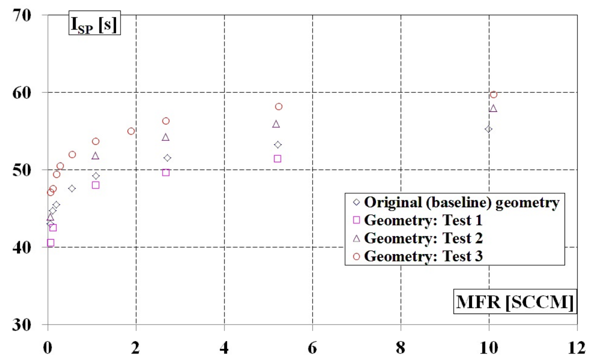

Figure 7: Zoom in the initial region of the previous figure.

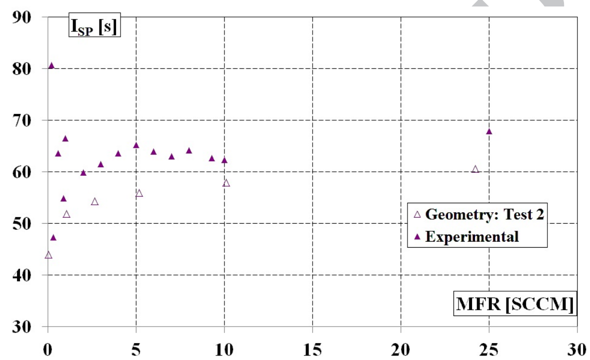

Figure 8: Specific impulse of the thruster as a function of the mass flow rate, comparison between numerical and experimental results.

pulse provided will also vary accordingly. Due to the need of very accurate evaluations of the thrust for the satellite positioning system, these effects needed to be evaluated in order to allow for a correct determination of the mass flow rate to be fed to the nozzle.

This determination required to perform a set of computations at different couples of gas temperature/nozzle temperature for the various flow rates. The temperature ranges that were selected for the computation of such maps were determined based on the mission profile. Of course, this mapping was performed only for the selected geometry since it required a large computational effort. The performance maps corresponding to two different mass flow rates are reported in Figg. 9 and 10, respectively. It can be observed that the increase of both temperatures leads to an increase of the specific impulse, providing thus large possible variations. The difference between the minimum and maximum values of I_{SP} that were obtained in the range of temperatures considered for the mapping could be as large as 15%, indicating thus a large variation of performance.

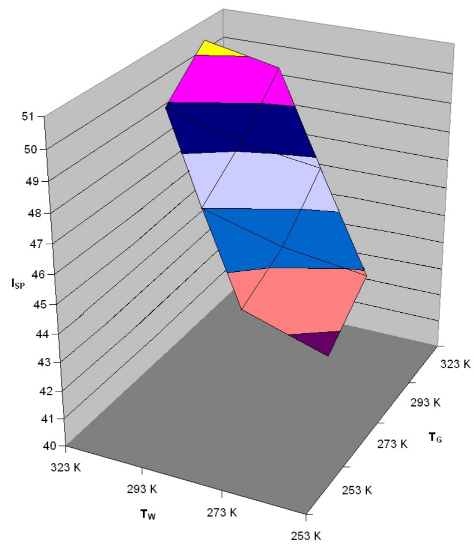

Figure 9: Specific impulse of the thruster as a function of the gas initial temperature (T_G) and of the nozzle temperature (T_W), low mass flow rate.

It can be observed that both maps have the same general shape, and it was checked that this is also true for all the computed maps corresponding to other flow rates. This suggests that it might be possible to obtain a single map if an appropriate nondimensionalization was performed. In order to investigate this possibility, data for all mass flow rates were scaled to the corresponding specific impulse at reference conditions.

Regression equations were obtained by multivariate linear regression analysis (least squares method) for every rescaled data set. It was found out that the general form of the equations is always the same, although small differences exist between the various regression values; this allowed to define a general non-dimensional equation for the nozzle performance map as a function of the considered temperatures.

5. Conclusions

The micro-thrusters designed through the method described here were implemented into the missions GAIA, LISA Pathfinder and MICROSCOPE;

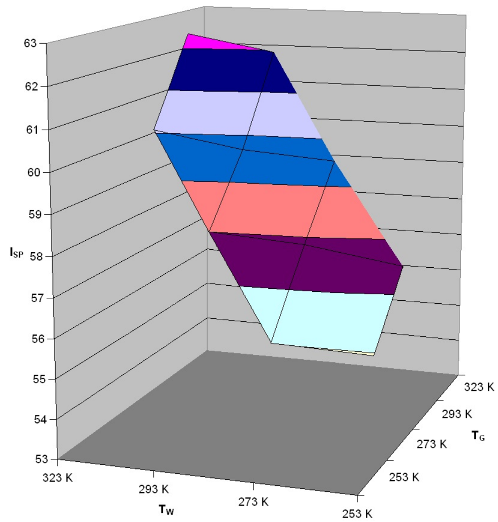

Figure 10: Specific impulse of the thruster as a function of the gas initial temperature (T_G) and of the nozzle temperature (T_W), high mass flow rate.

furthermore, they were selected for the mission EUCLID, for which the manufacturing phase is presently nearing completion.

In all of the flight missions presently in operation, the positioning system is performing within the mission parameters, thus providing a further *a posteriori* validation of the applied method.

It is to be observed, though, that the technique adopted to perform the matching between the continuum and the rarefied flow is quite complex and cumbersome, and due to the constraints it introduces it leads to a reduction of the computational efficiency; furthermore, the fact that a two-dimensional methodology was used for the rarefied flow analysis limits the possibilities of the method.

Future developments of the methodology will call for the development of a genuinely three-dimensional DSMC code, and for an automated matching procedure between the continuum and rarefied portions of the motion field. Such developments would allow to obtain a complete and reliable methodology for the design of space thrusters, which in turn would lead to better performance analysis and, ultimately, to improved design and optimization of the devices.

Acknowledgements

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